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Elevated Blood Lead Levels and Reading Readiness at the Start of Kindergarten

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KEY WORD

lead poisoning, school performance, screening—early childhood

ABBREVIATIONS

BLL—blood lead level
CI—confidence interval
GM—geometric mean
PALS-K—Phonological Awareness Literacy Screening–Kindergarten
PPSD—Providence Public School District
RIDH—Rhode Island Department of Health
SES—socioeconomic status

Dr McLaine contributed to the conception, design, analysis, and interpretation of data and the initial drafting and revisions of the article; Drs Navas-Acien and Agnew contributed to the design, analysis and interpretation of data and participated in the revision of the article; Ms Lee acquired and linked health and education data for this study, oversaw data quality, aided in interpretation of data, and participated in the revision of the article; Dr Simon contributed to the initial concept and design and acquisition and interpretation of data and participated in the revision of the article; and Dr Diener-West contributed to the analysis and interpretation of the data and participated in the revision of the article.

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WHAT'S KNOWN ON THIS SUBJECT: Blood lead levels well below 10 μg/dL are now recognized as causing adverse cognitive effects, including lower scores on standardized reading and math tests.

WHAT THIS STUDY ADDS: This is the first study to show that reading readiness early in kindergarten is independently associated with blood lead levels well below 10 μg/dL. Results suggest that lead exposure may have a larger impact on urban education than national estimates suggest.

abstract

FREE

OBJECTIVE: To evaluate the relationship between blood lead levels (BLLs) and reading readiness at kindergarten entry, an early marker of school performance, in a diverse urban school population.

METHODS: Kindergarten reading readiness test scores for children attending public kindergarten in Providence, Rhode Island, were linked to state health department records of blood lead testing by using individual identifiers. The study population (N = 3406) was 59% Hispanic. For each child, the geometric mean BLL was estimated by using all previously reported BLLs. Analyses were adjusted for gender, age, year enrolled, race, child language, and free/reduced lunch status as a measure of socioeconomic status.

RESULTS: The median geometric mean BLL was 4.2 μg/dL; 20% of children had at least 1 venous BLL ≥10 μg/dL. Compared with children with BLLs <5 μg/dL, the adjusted prevalence ratios (95% confidence interval [CI]) for failing to achieve the national benchmark for reading readiness were 1.21 (1.19 to 1.23) and 1.56 (1.51 to 1.60) for children with BLLs of 5 to 9 and ≥10 μg/dL, respectively. On average, reading readiness scores decreased by 4.5 (95% CI: −2.9 to −6.2) and 10.0 (95% CI: −7.0 to −13.3) points for children with BLLs of 5 to 9 and ≥10 μg/dL, respectively, compared with BLLs <5 μg/dL.

CONCLUSIONS: BLLs well below 10 μg/dL were associated with lower reading readiness at kindergarten entry. The high prevalence of elevated BLLs warrants additional investigation in other high-risk US populations. Results suggest benefits from additional collaboration between public health, public education, and community data providers. *Pediatrics* 2013;131:1081–1089

Childhood lead exposure has detrimental effects on cognition, including IQ, executive function, and delinquency.[1] Adverse effects have been found at levels well below 10 μg/dL, the "level of concern" set by the Centers for Disease Control and Prevention in 1991.[2] Cross-sectional and longitudinal studies have revealed significant effects of lead exposure on learning with the use of standardized school tests and functional measures of school performance, including reading and math test scores, reading at grade level, and graduation from high school.[3–8] This evidence is reflected in Centers for Disease Control and Prevention's recent establishment of a population-based reference value to target children with blood lead levels (BLLs) above the 97.5th percentile, which is currently a BLL of 5 μg/dL.[9]

Learning to read is critical to the entire process of formal education. Children who learn to read in first grade are more likely to be successful in applying their reading skills to other areas of learning[10] and with school performance in higher grades.[11] Learning to read successfully requires proficiency in phonologic processing skills (using the sounds of one's language to process written and oral language) and in the ability to decode new words.[12,13] The lack of these skills, not IQ deficits, has been associated with failure to learn to read.[14,15]

Reading readiness, therefore, is an early measure of a child's capacity to integrate cognitive ability and skills learned from a multitude of educational, enrichment, and environmental exposures. Kindergarten is a critical time for identifying children with poor reading readiness, and most US schools test children when they enter kindergarten in the fall. Many instruments are used to assess reading readiness, including the Phonological Awareness Literacy Screening–Kindergarten (PALS-K) test, used in our study (R. Blackwell-Bullock, MEd, Reading K-12, personal communication, 2009).

Associations between BLLs measured during early childhood and reading readiness in kindergarten have not been previously examined. We had an excellent opportunity to investigate this relationship with the use of public health and education monitoring data from Providence, Rhode Island. Strong partnerships between the Rhode Island Department of Health (RIDH), the Providence Public School District (PPSD), and the Providence Plan, a nonprofit community organization with extensive experience working with public and private databases, have been fostered for years, culminating in agreements to use available data to address larger social issues, such as school readiness. By linking individual data maintained by 2 public systems, health and education, we were able to examine the relationship between kindergarten reading readiness and measures of earlier lead exposure.

METHODS

Study Design and Data Linkage

This population-based study used linked data from children's kindergarten records and health records, including BLLs measured before kindergarten, to examine associations between past lead exposure and reading readiness in the fall of the kindergarten school year. The PPSD obtained 2 school data sets for 5211 children enrolled in kindergarten in Providence, Rhode Island, Public Schools during 3 school years (2004–2005, 2005–2006, and 2006–2007): school enrollment data and measures of kindergarten reading readiness based on results of the PALS-K test. The RIDH provided 2 data sets: blood lead screening data and data routinely collected at the time of birth.

The Providence Plan linked information from the 4 data sets by using a unique identifier (ID) created for each individual and making use of the child's school ID (assigned to each child by the PPSD) and the child's KIDSNET (Rhode Island's confidential, computerized child health information system) ID (assigned by the RIDH to every child for whom public health data are available in the KIDSNET system). Discrepancies were resolved by manual examination of the records and by confirmation with school or health department staff. As a final step, the Providence Plan generated a study ID for each child and provided deidentified data files for this study. The institutional review board of the Johns Hopkins Bloomberg School of Public Health reviewed our proposal and determined that this research was exempt.

Study Population

We excluded 644 children who had no BLL results and 74 who were repeating kindergarten (Fig 1). From the remaining 4493 first-time kindergarten children, we excluded 466 without PALS-K test results and 372 children with only 1 PALS-K score (fall only = 190, spring only = 182). We excluded children missing spring scores to allow for comparability with future analyses. We additionally excluded 3 children whose only lead measurement was an elevated capillary BLL, 173 children taught only in Spanish, 30 children enrolled in special education classes, and 43 inclusion students (special education students who receive instruction in regular education classrooms). The 3406 participants were similar to the original study population in BLLs, PALS-K results, and free/reduced lunch distribution (data not shown).

Demographic and School Data

Data on demographic characteristics (date of birth, gender, birth place, race, child's primary language, and child's status for the federal free and reduced-price school lunch program) and school (elementary school, kindergarten program [regular education, English as a second language, dual language

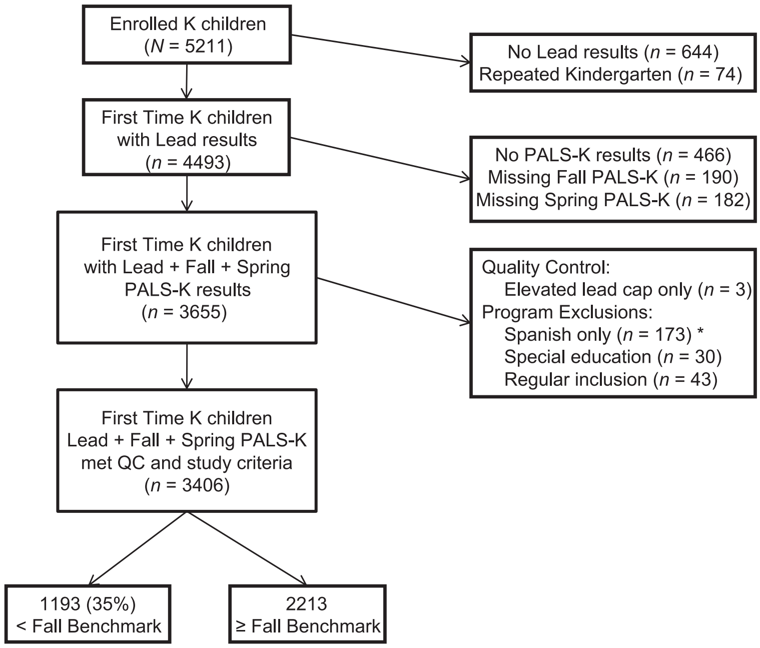

FIGURE 1
Study enrollment. *Including 14 Spanish inclusion students. K, kindergarten; QC, quality control.

programs], and school funding from the Federal Reading First program[16,17]) were collected at the time of the child's registration for school, verified by school officials, and entered directly into the PPSD's electronic data system. Free and reduced-price school lunch program status served as our variable for estimating socioeconomic status (SES), as is common in educational research.[18] Children from families with incomes at or below 130% and between 130% and 185% of the national poverty level are eligible for free or reduced-price lunch as part of the National School Lunch Program.[19]

PALS-K Test Data

The PALS-K test is a screening diagnostic and evaluation tool used to assess children's development of early literacy skills.[20] The cognitive elements examined by PALS-K are decoding, cipher knowledge, letter knowledge, concepts about print, and phonologic awareness.[21] PALS-K is a criterion-referenced assessment.[21] It has been used as the universal screening tool for Virginia since 1997 as well as in some school districts in all other US states and in 6 other countries (R. Blackwell-Bullock, MEd, Reading K-12, personal communication, 2009; ref 22). PALS-K is administered individually and in small groups in English by kindergarten teachers in the early fall and late spring of kindergarten.[20] Students who score below the fall benchmark (28 of 102 points) receive additional in-classroom instruction on a regular basis, focused on the areas of deficiency in specific cognitive elements (or subtests), for the duration of the school year. PALS-K total scores are compiled by summing results of 6 subtests, with a maximum possible score of 102 points.[23] Success at the end of kindergarten is based on a child achieving the spring benchmark (≥81 of 102 points).[24] The PALS-K instrument has been extensively field-tested in Virginia since 1997 across race/ethnicity, gender, and SES and found to provide valid and reliable measures of kindergarten readiness.[20]

The PPSD began use of PALS-K in 2002. Students were typically tested during a 2-week period in October. PALS-K results for individual children were reported electronically to Providence Plan. We checked total score computation, found 87 discrepancies (2.6%), and corrected them by using the PALS-K scoring protocol.[24]

Blood Lead Screening Data

The RIDH recommends annual testing for BLLs for children 9 to 72 months of age.[25,26] Rhode Island children are routinely tested for lead exposure by their primary care providers, and the results of BLL tests are sent by analyzing laboratories to the RIDH's Lead Elimination Surveillance System. Approximately 80% of BLL measurements reported to the RIDH during 1999–2005 were performed by 2 Clinical Laboratory Improvement Amendments–approved laboratories with a 1-μg/dL limit of detection for lead (A. Cardoza, Associates Degree in Computer Science, personal communication, 2009). BLL measurements reported as "below the minimal detection limit" (n = 553) were assigned blood lead values by using their respective laboratory minimal detection limit divided by square root of 2.[27] BLLs were available for 88% of children enrolled in the 3 kindergarten cohorts.

Blood lead samples were coded as venous (n = 15 326), capillary (n = 1212), or not coded (n = 11). Not coded samples were determined to most likely be venous samples and were retained in analyses. We evaluated the accuracy of capillary blood lead measurements ≥10 μg/dL (n = 206) by comparing them to venous BLLs drawn within 3 months. Less than half were retested, and only 26% of capillary values were confirmed. We removed all capillary BLLs ≥10 μg/dL from the data set, resulting in the removal of 3 children who had no other BLL reported. We kept capillary BLLs <10 μg/dL because these values were considered acceptable in clinical practice. Our data set consisted of 11 196 BLLs for 3406 children who were tested, on average, 3 times before kindergarten (mean [SD] = 3.2 [2.0]; range = 1–26). Most children (2899; 85%) had ≥2 BLL measures.

Birth Data

Birth data (birth weight, gestational age, maternal age and education, marriage status, and payer of record for the child's delivery), routinely abstracted from each child-mother pair's records by community health nurses who visit maternity hospitals 5 days per week, were available for a total of 3651 children.

Data Analysis

We used Stata 10.1 (StataCorp, College Station, TX) for the analyses. The geometric mean (GM) of BLLs for each child was estimated by using all of his or her blood lead measures available. We calculated median GM BLLs for all covariates, stratifying on fall benchmark status (fall PALS-K score above or below the benchmark).

We used linear regression models to estimate mean differences in PALS-K scores by GM BLLs. We also used Poisson regression with robust SEs to estimate the prevalence ratio of scoring below the PALS-K benchmark in the fall by GM BLLs. We modeled GM BLLs on the basis of dummy variables by using frequently used categories (<5, 5–9, and ≥10 μg/dL), refined categories (<2, 2, 3, 4, 5, 6, 7, 8, 9, and ≥10 μg/dL), and also on the basis of $\log_2$ transformations to evaluate changes in associations with a twofold increase in BLL, assuming a log-linear relationship. Models were adjusted for covariates known to affect reading readiness, including child characteristics (age, gender, race, child language), SES (free and reduced lunch status), and year of kindergarten (2004–2005, 2005–2006, 2006–2007). We conducted several sensitivity analyses including examining summary metrics of BLL (highest BLL at youngest age, a time-weighted average of BLL for children with ≥2 BLLs available,

TABLE 1 BLLs and Fall PALS-K Total Test Score by Study Population Characteristics

	N	%	GM BLL, Median (IQR), μg/dL	Mean (SD) Fall PALS-K Total Test Score
Study population characteristics				
Entire group	3406	100	4.2 (2.9–6.0)	41.2 (24.0)
BLL categories				
<5 μg/dL	2091	61.5	3.1 (2.2–4.0)	42.9 (23.9)
5–9 μg/dL	1098	32	6.3 (5.5–7.5)	39.5 (23.9)
≥10 μg/dL	217	6.5	11.7(10.8–14.2)	33.8 (23.3)
Individual demographic characteristics				
Gender				
Female	1679	49	4.2 (2.9–6.0)	42.5 (23.7)
Male	1727	51	4.2 (2.8–6.0)	40.1 (24.2)
Age at start of kindergarten				
<5 years, 3 months	901	26	4.2 (2.9–6.0)	37.1 (22.6)
5 years, 3 months, to <5 years, 6 months	881	26	4.0 (2.7–5.5)	39.7 (23.7)
5 years, 6 months, to <5 years, 9 months	888	26	4.2 (2.8–6.0)	43.7 (23.6)
≥5 years, 9 months	736	24	4.6 (3.1–6.6)	45.4 (25.2)
Race				
White	442	13	4.2 (2.7–6.0)	50.3 (25.1)
Black	707	21	5.0 (3.2–7.0)	46.9 (23.0)
Hispanic	2021	59	4.0 (2.7–5.6)	37.3 (23.0)
Other[a]	236	7	4.5 (3.0–6.5)	41.1 (24.2)
Child language				
English	2074	61	4.3 (3.0–6.1)	46.0 (24.0)
Spanish	1219	36	4.0 (2.7–5.5)	33.9 (21.9)
Other[b]	98	3	5.0 (3.5–8.0)	32.1 (21.9)
Missing	15	<1	3.9 (2.4–6.6)	43.3 (21.3)
Birthplace				
Rhode Island	2796	82	4.2 (2.9–6.0)	42.0 (23.8)
Other US state	424	12	4.0 (2.7–6.0)	39.1 (24.9)
Central/South America	100	3	3.9 (2.9–5.7)	31.2 (21.1)
Other country	57	2	6.3 (3.6–9.9)	38.4 (23.9)
Missing	29	1	4.0 (2.7–5.7)	44.1 (22.7)
School characteristics				
Kindergarten year				
2004–2005	870	26	4.0 (2.7–6.0)	37.9 (22.5)
2005–2006	1272	37	4.2 (2.9–6.0)	42.1 (24.3)
2006–2007	1264	37	4.3 (2.9–6.1)	42.7 (24.4)
Kindergarten program				
Dual language	115	3	3.9 (2.9–5.7)	36.2 (17.9)
English as a second language	568	17	4.2 (2.9–6.2)	25.2 (17.6)
Regular	2723	80	4.2 (2.8–6.0)	44.8 (23.9)
Reading First school				
Yes	891	26	4.2 (2.9–6.0)	40.9 (24.7)
No	2515	74	4.2 (2.9–6.0)	41.4 (24.4)
SES				
Free/reduced/pay lunch status				
Free	2713	80	4.3 (3.0–6.1)	39.3 (23.4)
Reduced	357	10	3.8 (2.5–5.2)	45.5 (24.5)
Pay	336	10	3.9 (2.3–5.6)	52.2 (24.5)
Birth data				
Birth weight category				
<1500 g	42	1	4.0 (2.8–6.0)	37.4 (21.4)
1500–2499 g	175	5	4.6 (2.8–6.0)	43.6 (25.8)
≥2500 g	2479	73	4.2 (2.9–6.0)	41.9 (23.7)
Missing	710	21	4.0 (2.8–6.0)	38.7 (24.4)
Gestational age				
<34 weeks	66	2	4.1 (3.0–5.7)	38.3 (23.4)
34–36 weeks	200	6	4.5 (3.0–6.2)	43.5 (25.3)
≥37 weeks	2430	71	4.2 (2.9–6.0)	41.9 (23.7)
Missing	710	21	4.0 (2.8–6.0)	38.7 (24.4)

TABLE 1 Continued

	N	%	GM BLL, Median (IQR), μg/dL	Mean (SD) Fall PALS-K Total Test Score
Maternal high school education				
No	1164	34	4.6 (3.1–6.5)	35.6 (22.3)
Yes	1437	42	4.0 (2.7–5.8)	46.8 (23.9)
Missing	805	24	4.0 (2.7–6.0)	39.4 (24.2)
Public insurance at birth				
No	608	18	3.9 (2.5–5.5)	48.3 (23.6)
Yes	2088	61	4.4 (3.0–6.2)	40.1 (23.5)
Missing	710	21	4.0 (2.8–6.0)	38.7 (24.4)
Parents married at child's birth				
Yes	731	21	3.8 (2.5–5.4)	46.0 (24.2)
No	1965	58	4.5 (3.0–6.2)	40.4 (23.5)
Missing	710	21	4.0 (2.8–6.0)	38.7 (24.4)

N = 3406. IQR, interquartile range.
[a] Asians comprise 92% of "other."
[b] Asian languages comprise 80% of "other."

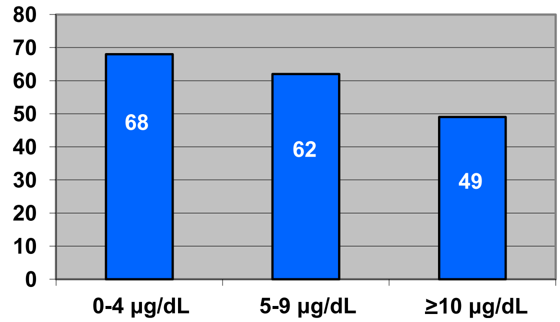

FIGURE 2
Proportion of children scoring above the fall PALS-K benchmark, by BLL.

BLL at 5 years) by using blood lead quartiles, adjusting for additional measures of SES in children with birth data (maternal education, public insurance at birth, and whether parents were married at birth), and evaluating potential effect modification by using interaction terms between BLLs and participant characteristics (all model covariates). Results based on an area under the curve approach were similar to those of GM BLLs (data not shown).

RESULTS

PPSD students represented a diversity of backgrounds, with 59% being Hispanic (Table 1). Although 61% of students spoke English as their primary language, >1 language was spoken in the homes of 43% of students. More than 90% of students qualified for the federal free or reduced-price school lunch program.

The median (interquartile range) GM BLLs were 4.2 (2.9–6.0) μg/dL (Table 1). Nearly 20% of the children had at least 1 BLL ≥10 μg/dL, and 69% had at least 1 BLL as high as 5 μg/dL, compared with national prevalence estimates of 1.4% and 7.4%, respectively.[28] BLLs were highest in blacks and lowest in Hispanics. BLLs were higher in children who spoke languages other than English or Spanish (80% of Asian descent), had measures of lower SES, and had total PALS-K fall scores below the benchmark. No trends in BLLs were observed by birth weight or gestational age.

Approximately 35% of students failed to achieve PALS-K benchmarks in the fall of the kindergarten school year (Table 1). Total fall scores were consistently lower for children who were male, of Hispanic ethnicity, enrolled in the English as a second language program, spoke Spanish or other languages, received free lunch, and had a GM BLL of ≥10 μg/dL. Total PALS-K fall scores were lower for children whose mothers had not graduated from high school or who had public insurance at the time of the child's birth and for children in the lowest birth weight and gestational age categories. PALS-K scores increased with kindergarten year and with age and were higher in white and black children than in Hispanic and other children. A total of 68% of children with BLLs <5 μg/dL achieved the PALS-K benchmark compared with 49% of children with BLLs ≥10 μg/dL (Fig 2).

In the fully adjusted linear regression model, we observed significant decreases in reading readiness of 4.5 points (95% confidence interval [CI]: −2.9 to −6.2) for children with GM BLLs of 5 to 9 μg/dL and of 10.1 points (95% CI: −7.0 to −13.3) for children with GM BLLs of ≥10 μg/dL, compared with children with GM BLLs <5 μg/dL (Table 2, model 5). The fully adjusted associations between other model covariates and the fall PALS-K summary score are shown in Table 3. The decrease in reading readiness in children with free lunch versus those who paid for lunch was 10.3 points (95% CI: −7.7 to −12.9), which is similar in magnitude to the difference between the highest and lowest BLL categories.

Compared with participants with BLLs <2 μg/dL, increasing BLLs resulted in progressive decreases in PALS-K scores (Table 2, Fig 3) with no evidence of a threshold. Children with BLLs of ≥10 μg/dL had a PALS-K score that was 13 points lower (corresponding to half of the SD of PALS-K scores) compared with children with BLLs <2 μg/dL.

The fully adjusted prevalence ratios for scoring below the fall PALS-K benchmark (score = 28) were 1.21 for children

TABLE 2 Mean Difference (95% CI) in Fall PALS-K Scores by BLL

	Group Size, *n*		Model 1	Model 2	Model 3	Model 4	Model 5
	Below Fall BM	Above Fall BM					
GM BLL categories	1193	2213					
0–4 μg/dL	668	1423	0.00 (Reference)	0.00 (Reference)	0.00 (Reference)	0.00 (Reference)	0.00 (Reference)
5–9 μg/dL	415	683	−3.4 (−5.2 to −1.7)	−3.8 (−5.5 to −2.1)	−4.9 (−6.6 to −3.2)	−4.8 (−6.5 to −3.1)	−4.5 (−6.2 to −2.9)
≥10 μg/dL	110	107	−9.1 (−12.5 to −5.8)	−9.9 (−13.2 to −6.6)	−11.7 (−15.0 to −8.5)	−11.1 (−14.3 to −7.9)	−10.1 (−13.3 to −7.0)
P trend			<.001	<.001	<.001	<.001	<.001
r^2			0.0109	0.0380	0.0904	0.1150	0.1345
Refined GM BLL categories[a]	1193	2213					
1 μg/dL	83	213	0.00 (Reference)	0.00 (Reference)	0.00 (Reference)	0.00 (Reference)	0.00 (Reference)
2 μg/dL	197	416	−2.6 (−5.9 to 0.8)	−2.1 (−5.4 to 1.2)	−2.4 (−5.6 to 0.8)	−2.8 (−5.9 to 0.4)	−2.7 (−5.8 to 0.5)
3 μg/dL	209	409	−3.8 (−7.1 to −0.5)	−3.6 (−6.8 to −0.3)	−3.8 (−7.0 to −0.7)	−4.1 (−7.3 to −1.0)	−3.3 (−6.5 to −0.2)
4 μg/dL	179	385	−2.7 (−6.0 to 0.7)	−2.6 (−5.9 to 0.7)	−3.2 (−6.4 to 0.04)*	−3.6 (−6.8 to −0.4)	−2.7 (−4.9 to 4.7)
5 μg/dL	148	272	−4.4 (−7.9 to −0.8)	−4.6 (−8.1 to −1.1)	−5.6 (−9.0 to −2.2)	−5.6 (−9.0 to −2.3)	−5.0 (−8.4 to −1.7)
6 μg/dL	130	193	−6.7 (−10.5 to −3.0)	−6.7 (−10.4 to −3.0)	−8.4 (−12.1 to −4.8)	−9.0 (−12.6 to −5.4)	−8.1 (−11.7 to −4.5)
7 μg/dL	56	91	−6.4 (−11.1 to −1.6)	−7.2 (−11.9 to −2.6)	−8.9 (−13.5 to −4.4)	−9.3 (−13.8 to −4.9)	−8.2 (−12.7 to −3.8)
8 μg/dL	55	79	−8.5 (−13.3 to −3.6)	−8.5 (−13.3 to −3.7)	−10.0 (−14.7 to −5.3)	−10.3 (−14.9 to −5.6)	−9.3 (−13.9 to −4.7)
9 μg/dL	26	48	−7.1 (−13.1 to −1.0)	−6.8 (−12.8 to −0.8)	−8.0 (−13.9 to −2.2)	−7.9 (−13.7 to −2.2)	−7.0 (−12.7 to −1.3)
≥10 μg/dL	110	107	−11.7 (−15.9 to −7.5)	−12.3 (−16.4 to −8.1)	−14.5 (−18.5 to −10.4)	−14.1(−18.1 to −10.1)	−12.7 (−16.6 to −8.7)
P trend			<.001	<.001	<.001	<.001	<.001
r^2			0.0135	0.0402	0.0933	0.1187	0.1372
Log_2 GM BLL doubling model, per twofold increase	1193	2213	−3.2 (−4.2 to −2.3)	−3.5 (−4.4 to −2.5)	−4.1 (−5.0 to −3.1)	−4.0 (−4.9 to −3.0)	−3.5 (−4.4 to −2.6)
P			<.001	<.001	<.001	<.001	<.001
r^2			0.0129	0.0394	0.0911	0.1165	0.1343

N = 3406. Model 1 was unadjusted; model 2 was adjusted for age at start of kindergarten, gender, and year; model 3 was additionally adjusted for race; model 4 was additionally adjusted for child language; model 5 was additionally adjusted for free/reduced lunch status. BM, benchmark.

[a] Refined GM BLL categories: 1 μg/dL = 0.7–1.99; 2 μg/dL = 2.0–2.99; 3 μg/dL = 3.0–3.99; 4 μg/dL = 4.0–4.99; 5 μg/dL = 5.0–5.99; 6 μg/dL = 6.0–6.99; 7 μg/dL = 7.0–7.99; 8 μg/dL = 8.0–8.99; 9 μg/dL = 9.0–9.99.

* *P* = .053.

with GM BLLs of 5 to 9 μg/dL (95% CI: 1.19–1.23) and 1.56 for children with GM BLLs of ≥10 μg/dL (95% CI: 1.51–1.60), compared with children with GM BLLs of <5 μg/dL (Table 4, model 5).

DISCUSSION

This is the first study of the association between childhood lead exposure and reading readiness at the start of kindergarten. We found a clear dose-response relationship between exposure to lead in early childhood, measured by the GM of multiple blood lead measures, and reading readiness at the beginning of kindergarten, measured by the total PALS-K score. The negative association of blood lead with kindergarten reading readiness remained strong after adjustment for demographic factors, language, and SES. Associations were observed well below 10 μg/dL, with no evidence of a threshold. Other studies[3–5] have reported that the change in the BLL-reading score relationship is not linear. Like Miranda et al's[8] observations of end-of-grade test scores, the magnitude of the difference in fall PALS-K scores associated with lead exposure in our study was similar to the difference associated with eligibility for free and reduced lunch, a measure of low SES.

Race and language are important predictors of reading and reading readiness in the United States. Student populations of urban school districts like Providence are very diverse, with white students often in the minority and many students speaking languages other than English. This diversity, coupled with poverty, creates unique challenges for educators who wish to narrow the gap in educational performance. Most educational researchers have focused attention on differences between black and white children without examining the size of the achievement gap for other racial or ethnic groups, notably Hispanic or Asian children.[29] Because we had data on language, race/ethnicity, and birthplace

TABLE 3 Adjusted Mean Difference (95% CI) in Fall PALS-K Summary Score by Participant Characteristics From a Multiple Linear Regression Model

	Mean Difference	95% CI
BLL		
0–4 μg/dL	0.00	Reference
5–9 μg/dL	−4.51	−6.16 to −2.85
≥10 μg/dL	−10.13	−13.30 to −6.96
Gender		
Female	0.00	Reference
Male	−2.80	−4.31 to −1.30
Year		
2004–2005	0.00	Reference
2005–2006	3.53	1.58 to 5.49
2006–2007	3.71	1.74 to 5.69
Age group		
<5 years, 3 months	0.00	Reference
5 years, 3 months, to <5 years, 6 months	2.68	0.60 to 4.77
5 years, 6 months, to <5 years, 9 months	6.57	4.49 to 8.65
≥5 years, 9 months	8.26	6.03 to 10.49
Race		
Hispanic	0.00	Reference
White	6.85	4.23 to 9.47
Black	6.05	3.77 to 8.32
Other	2.51	−1.18 to 6.20*
Language		
English	0.00	Reference
Spanish	−8.43	−10.41 to −6.44
Other	−12.74	−17.91 to −7.57
Free/reduced/pay lunch status		
Pay for lunch	0.00	Reference
Reduced lunch	−4.18	−7.56 to −0.80
Free lunch	−10.31	−12.91 to −7.71
Constant[a]	50.41	46.37 to 54.45
R^2	0.1345	

Final model adjusted for GM BLL category, gender, year, age at time of test, race, child language, and free/reduced lunch status.

[a] Refers to the average score for a 5- to 5-1/4-year-old Hispanic female, speaking English, who pays for lunch, and with a BLL of 0 to 4 μg/dL in 2004–2005.

* $P = .182$.

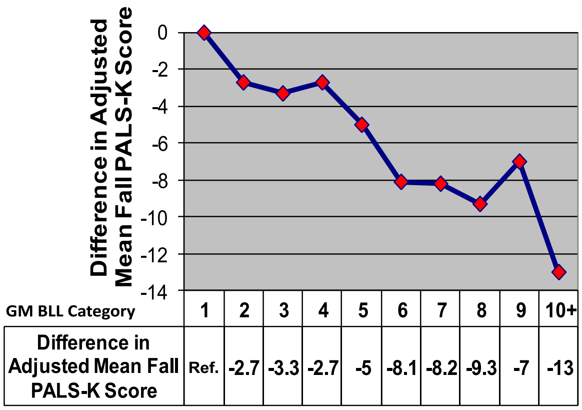

FIGURE 3
Adjusted differences in mean fall PALS-K scores between refined GM BLL categories compared with the reference category (<2 μg/dL). Linear regression model was adjusted for age at the start of kindergarten, gender and year, race, child language, and free/reduced lunch status.

available at the individual child level, it was possible to examine the association of lead and reading readiness within this diverse urban population without excluding children on the basis of race/ethnicity.

One in 5 (20%) Providence public school kindergarteners in our study had at least 1 BLL ≥10 μg/dL; 67% had at least 1 BLL ≥5 μg/dL. These results are markedly higher than NHANES estimates from the same time[28] and suggest that national population estimates may seriously underestimate the lead problem in urban schools.

Exposure to lead in older housing may help to explain some of the disparities in reading readiness seen in at-risk urban children in the United States. The higher BLLs seen in this study may be associated with living in lower quality housing, higher maternal lead levels, higher exposure to secondhand smoke,[30] or other unmeasured factors. Children eligible for a free school lunch would more likely live in lower quality housing compared with children paying for their lunch. Our results suggest the need to continue to emphasize primary prevention efforts focused on older housing and to evaluate the effectiveness of these public health measures in protecting young children.

We were able to conduct this study because of the following: (1) the high level of BLL screening penetration in Providence and (2) the ongoing relationships and strong cooperation between the state health department, local public schools, and a local community data provider, which made data linkage possible. Such relationships provide opportunities to link existing health and education data sets and to potentially identify other critical associations between environmental factors, health, and educational success at a relatively low cost.

The high rate of lead screening among kindergarten students (88%) suggests that Rhode Island's public health leadership and partnership with private providers have been successful. Unlike other states, the RIDH maintains childhood lead screening information in a central registry (KIDSNET) that also includes individual child data on 9 public health programs, including child immunization records.[31] Having online access to blood lead testing results for individual children may encourage more screening of at-risk children, particularly children who move and change providers frequently.

Our results suggest the need to evaluate current screening approaches for early reading intervention and to determine whether adding a history of elevated BLL could improve targeting of children who are at risk of school failure and are not presently being captured in that system. The use of a population-based approach to target additional early childhood education opportunities to communities where large proportions of children have elevated BLLs might be cost-effective.

TABLE 4 Prevalence Ratio of Scoring Below the PALS-K Fall Benchmark (95% CI) by BLL Categories

	Group Size, *n*		Model 1	Model 2	Model 3	Model 4	Model 5
	Below Fall BM	Above Fall BM					
GM BLL categories	1193	2213					
0–4 μg/dL	668	1423	1.00 (Reference)	1.00 (Reference)	1.00 (Reference)	1.00 (Reference)	1.00 (Reference)
5–9 μg/dL	415	683	1.18 (1.16–1.21)	1.20 (1.18–1.22)	1.23 (1.21–1.25)	1.22 (1.20–1.25)	1.21 (1.19–1.23)
≥10 μg/dL	110	107	1.58 (1.54–1.63)	1.62 (1.57–1.66)	1.66 (1.62–1.71)	1.61 (1.56–1.65)	1.56 (1.51–1.60)
Log GM BLL doubling model, per twofold increase	1193	2213	1.18 (1.17–1.19)	1.19 (1.18–1.20)	1.20 (1.19–1.21)	1.19 (1.18–1.21)	1.17 (1.16–1.19)
P			<.001	<.001	<.001	<.001	<.001

N = 3406. Model 1 was unadjusted; model 2 was adjusted for age at start of kindergarten, gender, and year; model 3 was additionally adjusted for race; model 4 was additionally adjusted for child language; model 5 was additionally adjusted for free/reduced lunch status. All values were significant at *P* = .001. BM, benchmark.

Strengths of this study include the following: the sample size; the availability of multiple BLL tests for each child; the quality of school enrollment data, birth data, and measurements of kindergarten reading readiness; and high-quality linkage of multiple data sets. However, data were originally collected for other purposes. Limitations include the few measures of reliability for BLL surveillance data and the availability of PALS-K in English only; a Spanish version of PALS-K was undergoing field testing during our study.[32] Our limited measures of SES and indicators of the enrichment of the child's early education and home environment, important for future studies,[20] may inadvertently result in residual confounding.

CONCLUSIONS

These results suggest that lead exposure at levels well below 10 μg/dL contributes to decreased reading readiness at kindergarten entry. The finding of a high prevalence of elevated BLLs in this urban school district warrants attention to other potentially high-risk urban populations. We linked kindergarten reading readiness and child health data to evaluate a diverse population of schoolchildren. The successful collaboration between public health and public education agencies and community data providers presents a model for other jurisdictions to consider. Future evaluation of student performance on end-of-grade tests later in elementary school (third and fourth grades) in this diverse cohort could help us to better understand the long-term impacts of both kindergarten reading readiness and childhood lead exposure on school success.

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